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Title: YIP: Fundamental Limitations on Quantum Noise Reduction in Optical Fibers

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ONR SPONSORED RESEACH ACCOMPLISHMENTS:

Long-term Research Objectives:

Recent explosive advances in the manufacturing of optical fibers and related fiber optic components have made them essential to many emerging technologies, including high speed communication systems, bandwidth intensive data transmission, and sensor applications. As these technology fields progress toward achieving ultra-high data rate transmission and enhanced sensitivity, the performances of key fiber optic devices and systems are rapidly approaching fundamental physical limitations. Our overall objective in this ONR sponsored research is to explore the physical nature of noise processes in optical fibers, in particular quantum fluctuations, and reach a level of understanding that can be employed in the future engineering of sensors and networks.

Summary of Accomplished Research:

Quantum Noise of Solitons in Optical Fibers

The performances of fiber optic based devices and systems have rapidly approached fundamental physical limitations. The thrust of our research effort addresses questions regarding the physical nature of nonlinear noise processes in optical fibers and experimental methods to reduce or "squeeze" the quantum noise. We exploit nonlinear optical processes to achieve quantum noise reduction for sensitivity enhancement applications in photon number and phase measurements. By performing experiments that manipulate the quantum fluctuations associated with the optical field we also probe the fundamental limitations of the system. In particular, my early experiments on quadrature squeezing with pulses in optical fibers required overcoming guided acoustic wave noise that severely limited prior measurements [1]. **This work led to a record quadrature quantum noise reduction (70%) by a factor of two over previous results and the generation of squeezed vacuum** [2,3]. Our current research at Princeton with my graduate student Dmitriy

Krylov has employed a novel scheme for generating amplitude (number state) squeezed solitons in an asymmetric fiber Sagnac loop interferometer. In our work we conclusively demonstrated that this squeezing is a result of the interference between the soliton and the dispersive wave. **We directly measured a record amount, 5.7dB, of quantum amplitude noise reduction with solitons** [4]. Our technique also suppresses all the classical amplitude noise which is about 3dB above the shot noise level, leading to a total noise reduction of nearly 9dB. Soliton communications systems, which employ direct detection, may benefit from this simple noise suppression module. We have also shown that the squeezing is not limited to solitons and can occur in the normal dispersion regime [5]. The photon number squeezing is fundamentally limited by noise arising from the soliton self-Raman-shift in fiber. Our work probes the Raman noise and dispersion dependent limitations on squeezing and applications of soliton number states to sensors, quantum non-demolition (QND) measurements, quantum communications, and noiseless amplification.

Soliton Lasers

The current deployment of solitons in fiber optic transmission systems is a result of the soliton pulse intriguing capability to maintain shape and width (both temporally and spectrally) in the presence of group velocity dispersion (GVD) and nonlinear self phase modulation (SPM). Solitons are also robust to various perturbations such as loss, imperfect launch conditions, timing and frequency shifts. In my research I have focused on the propagation dynamics of solitons within the controlled environment of a laser cavity. A modelocked laser cavity is essentially a perfectly periodic transmission system featuring the same perturbations occurring in actual systems without the randomness. We demonstrated the first modelocking of solid state (Cr^{+4}:YAG) and fiber lasers (Er/Yb) in the 1550nm region using a novel low loss ultrafast saturable absorber [6,7,8]. My work in this area with my graduate student Brandon Collings and collaborator from Bell Labs Wayne Knox led to a design of novel modelocked lasers with intracavity pulses that are truly fundamental solitons. The combination of low perturbation and strong soliton behavior in the laser enabled the initial observation and understanding of several effects that are indiscernible within most lasers. **Specifically, we demonstrated for the first time laser pulses that remain transform-limited despite large changes in the average cavity dispersion, pulse width, spectral bandwidth, and pulse energy.** By comparison, the commonly reported behavior in most other lasers is that the pulses become chirped if the cavity GVD is varied. The unique behaviors represent a significant contribution to the understanding of pulsed lasers and solitons systems. In addition, these compact cavities can support harmonic modelocking and thus have practical applications as high-speed (multi-gigahertz) sources for optical networks.

In our experiments on soliton lasers which includes solid state and fiber cavities, we observe soliton quantization and harmonic operation. The goal of my own work has been to develop a physical model that explains the self ordering leading to equal spacing between multiple pulses in the cavity. We have shown theoretically that the interaction of multiple intracavity soliton pulses with the small and slow dynamics of the gain medium causes passive and stable alignment of the pulses during harmonic modelocking[9]. Our physical model represents a new approach compared with previous work that was based on other phenomena such as soliton-soliton interaction, electrostriction, and dispersive wave coupling to explain the harmonic operation. None of the previous models could be successfully applied to our experiments, which explored a new regime of modelocked lasers with extremely low perturbations.

In my work on modelocked fiber lasers with Nathan Kutz (post-doc) we developed a theory for the modelocking pulse dynamics in a fiber laser with a saturable absorber. **The theory applies in both the normal and anomalous dispersion regimes and provides a model, which has been compared directly with experimental results for the first time.** Quantitative agreement is achieved in both dispersion regimes. The modelocking theory we developed extends beyond the qualitative description of the master modelocking equation. We provided a quantitative model, which has been utilized as a powerful design tool in evaluating the performance of fiber lasers modelocked in the normal and anomalous dispersion regimes [10].

My research efforts have also concentrated on high repetition rate modelocked Erbium doped fiber (EDF) lasers as reliable and compact sources for network transmitters in the 1550nm spectral region. The wide optical bandwidth generated by a single modelocked laser pulse can be further partitioned into a large number of channels for WDM applications, an approach which may be economically advantageous over employing a large bank of individually selected CW sources. Our unique short cavity Erbium/Ytterbium (Er/Yb) fiber laser is passively modelocked with a saturable Bragg reflector (SBR) producing femtosecond soliton pulses at multi-gigabit repetition rates. **By nonlinear propagation with dispersion management we have broadened the laser's output spectrum to 30nm which can support 40 independent wavelength channels from a single source** [11].

Chirped Soliton Propagation in Optical Fibers

The propagation of chirped pulses in optical fibers is of great interest due to the recent advancements in dispersion-managed communications systems. We demonstrate in this work that propagation in low dispersion fiber can produce phenomena, which are both of practical and fundamental interest. In particular, when a pre-chirped pulse is injected into low-dispersion anomalous fiber with a sufficiently strong chirp, the pulse will break up into a train of solitons, which propagate away from the center-position of the original pulse. In this break-up process, the ejected solitons are ordered according to height: the taller soliton pulses propagate faster than the smaller ones. **We have shown the first numerical and experimental evidence demonstrating explicitly this break-up phenomena** [12]. The numerical simulations are performed with my student Suzanne Sears and with Kutz (now at Univ. of Washington), while the experiments are done in my laboratory by graduate students Krylov and Leng. Agreement between the zero-dispersion limit theory of the nonlinear Schrodinger equation with chirp, numerical simulations, and experiment is excellent. The result is both of practical concern for limitations of dispersion-managed systems and fundamental in exhibiting a new phenomena associated with nonlinear optical fiber propagation. **We show soliton breakup under a strong symmetric perturbation. This is an example of symmetry breaking in a nonlinear optical system.**

We are currently in the process of extending this work, in collaboration with Segev's group here at Princeton, to **demonstrate the existence of fractals in this physical system [13]**. By repeating the conditions for break-up in more that one propagation stage we can potentially show (quasi) self-similarity on successive scales.

Vector Solitons

Despite the fact that "single" (radial) mode optical fiber supports two orthogonal polarization modes, soliton propagation in optical fiber is often treated as a scalar problem and the vector nature of light is ignored. Although this would be valid if the fiber were truly isotropic, in reality it is always slightly birefringent due to strain, bends, etc. For solitons to propagate with a uniform, non-evolving polarization state the phase velocities must be locked, resulting in a soliton that

preserves its polarization state (as well as its pulse shape) in the presence of birefringence. However, since the birefringence of standard single mode fiber is generally randomly distributed and propagation over long distances is accompanied by losses, clear experimental study of polarization locked solitons in transmission systems is difficult.

In our modelocked fiber lasers, the stable balance between the linear birefringence and (Kerr) nonlinear birefringence of an intracavity soliton causes the polarization state of that pulse to remain fixed despite the birefringent environment. In our work performed in a collaboration with Steve Cundiff (at Bell, now at U. Colorado), Wayne Knox and my student Collings, **we have observed the first such polarization-locked vector solitons in a modelocked fiber laser** [14]. Although such fixed polarization solitons have been the subject of theoretical conjecture they have not previously been experimentally observed [15,16]. This modelocked fiber laser provides a unique system that is nearly conservative and allows monitoring of the pulse during propagation over an essentially infinite distance. **Our experiments in a relatively short, very low loss, fiber cavity also produced the most lucid experimental observation to date of the Kerr nonlinearity induced instability of light polarized along a principal axis of a birefringence fiber.**

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PUBLICATIONS RESULTING FROM ONR SPONSORED RESEARCH:

JOURNALS

1. B. C. Collings, S. T. Cundiff, N. N. Akhmediev, J. M. Soto-Crespo, K. Bergman, and W. H. Knox, "Polarization-locked vector solitons in a fiber laser: experiment," to appear in *Journal of the Optical Society of America B.*

2. J. M. Soto-Crespo, N. N. Akhmediev, B. C. Collings, S. T. Cundiff, K. Bergman, and W. H. Knox, "Polarization-locked vector solitons in a fiber laser: theory," to appear in *Journal of the Optical Society of America B.*

3. D. Krylov, L. Leng, K. Bergman, J. C. Bronski, and J. N. Kutz, "Observation of the break-up of pre-chirped N-soliton pulses in an optical fiber," *Optics Letters*, 1191, **24** (1999).

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